

OBSERVATIONS ON MODERN WIND-ELECTRIC POWER PLANTS

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16. Abstract The author maintains that with the development of the "aeronautical" type windmill design, the installation of wind-powered electricity plants would be feasible for Italy undergoing post-war reconstruction. He believes it is possible to build from 200 to 300 small-capacity power plants for a total output of 10,000 to 15,000 kW in areas of Italy which have the minimum necessary wind speed of 5.5 m/sec. Among the designs required for such wind-electricity plants are windmill blades with variable pitch, automatic pitch con- trol system which does not use the costly servomotor, and reversible wheels. He asserts that these features enable a windmill of limited orientability to function with high efficiency. He also discusses the effect of wind rose patterns, the surface area of the blade, and some possible local uses of the electricity produced by such plants.		
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After pointing out the advantage the construction of wind- /494* electric power plants, which already exist in the USSR, Germany, and the U.S. among other places, can bring to Italy at this time, we define the main conditions necessary for a reasonable installation, giving prominence to the convenience of using wind-powered electricity for well-organized local utility services.

We discuss the practical problem of pitch regulation, or inclination, of the blades of the wind-driven wheel, stressing the necessity of adopting the reversible wheel, which allows for a considerable reduction in the construction cost of the support tower and also enables a more adaptable and effective functioning.

The question of wind-electric power plants deserves to be studied closely in the present stage of national reconstruction, since difficulties in developing new exploitation methods for hydroelectric energy are well-known and obvious (high cost of fixed operations, few promising water resources, etc.), and, on the other hand, the high price of liquid and solid fuels makes the production of thermoelectric energy very burdensome even for simple supplementary or subsidiary purposes.

The wind-electric power plant enables the realization of power outputs higher than those of air motors for direct and isolated utilization (mills, sawmills, pumps, etc.). It holds the great advantage of supplying electricity on-site, and is free of the restrictions of mechanical transmissions which are substituted by short electrical conduits. The wind-driven wheel can be installed at a most convenient site even removed from a

*Numbers in the margins indicate pagination in the foreign text.

population center, which always has an unfavorable influence on the local anemological condition. For example, at the University Observatory in Messina, the average wind speed is 3.5 m/sec, while at the Maritime Defense Station, in a more open locality, it reaches 4.3 m/sec, which represents a considerably larger energy output (almost double).

The larger power output attainable with the wind-electric power plant makes the utilization of wind more significant and economical, in comparison with the power obtained up to now with isolated devices, and it makes more varied and widespread the utility services that it can sustain.

Small wind-electric units have been operating for some time in every part of the world for charging storage batteries designed for domestic lighting.

Until now, however, the usefulness of wind-electric plants of considerable size has been challenged, especially by the experts. Thus, Lavagnolo, in his worthy handbook [1], expresses misgivings about wind-electric "power stations," and Jasinski [2] arrives at the assertion that he prefers ten power plants of 20 kW to only one of 200 kW.

It is naturally necessary to agree with him there!

The realization of wind-electric power stations, even those of modest power output, is made possible today only in relation to those aerodynamic and structural principles which aeronautical technology has established in its own right in recent times, as characterized by the prodigious progress in automatic flight control.

While we were building only very heavy and inefficient sheet-metal wheels with a large number of blades, it was natural that the power plant had rudimentary and limited properties, as this construction system presented prohibitive drawbacks for large units.

Today, on the other hand, with structures of the "aeronautical type" we can build without difficulty large and very fast rotors with three or four blades capable of driving electrical generators of up to 100 kW and higher, which are suitable for a considerable amount of utility services.

Thus the wind-electric power plant leaves obscurity behind to rise to a certain prominence, and to begin supplying small local centers such as factories, small industrial complexes, harbors, and so on, especially if they are deprived of access to a good distribution network of electrical energy.

It is true that one should look a little farther: we do not lack projects for colossal towers, for wheels over 100 m in diameter and power outputs of 2000 to 3000, and even 20,000 kW [3, 4, 5]. But this is, in my opinion, of a completely futuristic nature, since even if the new methods solve many problems inherent to air motors, they exaggeratedly increase the dimensions of these uncertainties, and the dangers are revived anew; and, at the same time, with the exaggerated increase in power, the advantage of the reduced distribution network disappears, which is the favorable characteristic of our system.¹

As I have dedicated myself to the study of air motors for many years, I may be permitted to summarize and discuss data that are essential to the question of the "blue coal" with

¹Above all, the angular velocity of the wheel decreases too much, making its connection with high-speed generators very difficult.

particular regard for our national situation.

General Possibilities of Wind-Electric Power Plants

Table 1 shows in summary, for different values of the wheel diameter expressed in meters, the power extractable for wind speeds of 5 and 10 m/sec, respectively, which is based on the assumption of good normal efficiency.²

TABLE 1.

Diam	8	12	16	20
kW	2/15	4.4/35	7.3/58	16/128

In order to assess the suitability of an installation, it is necessary to have, as is obvious, reliable data on the anemological condition of the selected site.

The usual anemological readings indicating the total course of the wind [9] allow an approximate calculation of its average velocity V_m and thus provide the data essential for the final decision.

However, before drawing the final conclusion, the problem must be considered from many aspects which we will explain briefly:

1) One may note that the average velocity V_m calculated from data on the anemograph is not the velocity which is effective on energy-related results, but in reality, a little less. As

² Apart from the criterion of aerodynamic efficiency, suitable power coefficients are used. See Nerli and Serragli, [6, 7].

the work supplied by the air motor is proportional to V^3 , we must effectively consider:

$$V_m = \left[\frac{1}{T} \int_0^T V^3 dt \right]^{1/3}$$

in which T is time.

If the diagram of the frequencies is known, the calculation 7495 of the graph of the effective V_m becomes faster.³

2) Reasons of safety and practicality call for the exclusion of the total utilization of maximum velocities V over 12-15 m/sec, something which occurs with particular devices which we will mention later. The frequency of these is rather low, but the energy magnitude, on the other hand, is considerable.

It can be calculated that in this manner we come to lose about 20-30% of the total performance.

3) It is useless to consider a wind-electric installation if there is no effective requirement in the locality for energy, and if this requirement does not conform to the particular discontinuity in the service provided by the wind.

The integration of a wind-electric unit for the purpose of obtaining a continuous service requires the availability of a 100% supplement at all times. That is to say, in my opinion, it becomes unfeasible from the economic standpoint. Perhaps some commercial electricity company could consider resorting to the wind for some of its specific temporary needs; but generally speaking, the local user who is supplied solely by a

³See the worthy work of Engineer Panunzio, [9, Fig. 5].

wind-driven plant should, by necessity, adapt himself to the wind.

Consequently, in the project for a wind-electric power station, it is of the highest importance to establish how to employ the energy produced for a variety of uses in such a way as to enable an effective utilization of 75% and possibly even greater.

Generally, for high V, one can design the generator to produce motive force for agricultural or industrial operations, which are always of such a nature that they could be postponed (ploughing, sawmills, mills, etc.).

For a low V (not less than $1/3$ of the total), the generator must function automatically for a suitable and reliable recovery service such as charging batteries, lifting water with pumps, etc.

Only in this way, as Keller [10] demonstrated, can one arrive at organizing an economical production, which always requires a margin for accumulation, although the margin may be small (see Fig. 9 below).

4) The power plant must be constructed under special technical criteria to which we will refer later; criteria which are necessary not only because the plant would become reasonable from a general point of view, but also because it would have a true economical value.

It is necessary to mention at the outset and frankly that costly innovations, even if they are ingenious and elegant, are not acceptable. The competitor of the wind-electric power plant is formidable (regular distribution network), and it makes one revise miscalculated estimates.

With the provision of the considerations mentioned above, taking into account the present costs (understandably with obvious reasonable modifications for the future), I believe that I can assert conclusively that a wind-electric power plant of 15-100 kW power output becomes economically feasible, and can almost compete with the average regular network, only in places where there is at least

$$V_m \geq 5.5 \text{ m/sec}$$

It suffices to consult the bulletins from the Brera, Montcalieri, etc. Observatories to see that there is no wind-electric feasibility for the Padana valley and its adjacent areas ($V_m = 1-2 \text{ m/sec}$).

The Venetian coast, even in the hinterland, offers good possibilities, however. In general, the coastal zones of central and southern Italy and the islands have many spots suitable for efficient installations.

As far as the Appenines are concerned, the case of Mt. Cimone was studied, as well as some other locations that are open on all sides.

But in the mountains, currents are quite unstable, and the maximum speeds are excessively high and dangerous for the endurance of the wheel.

Naturally, there are favorable localities such as the Netherlands, the Rheinland, etc., and above all, the famous wind power station at Balaclava in the Crimea⁴, where the V_m can reach 8 m/sec, a figure which would make an installation of any type economical.

⁴About this fundamental and fortunate installation, most elaborate details are given in electrotechnological publications around the world (from us, the journal L'elettrotecnica, etc.). For a summary, see [11].

But still respectable, for example, is the anemological condition of our Tripoli, which reaches $V_m = 6 \text{ m/sec}^5$.

Localities which reach $V_m = 5 \text{ m/sec}$ are not lacking in Italy, but it would take too long to discuss here the anemological conditions for every single region of our country. One can say approximately that it is possible to install in our country a total power output of about 10,000 to 15,000 kW, distributed among at least 200 to 300 power plants for non-continuous services, as I have said, which are still on the whole appreciably useful in relation to the present circumstances.

Technical Problems Concerning the Wind-Electric Power Plant

They are varied and considerable. It is worth taking pains to summarize briefly, with references to the bibliographic notes for particulars, some of those which have been illustrated, though briefly, in the figures.

First of all, as I have said, the old sheet-metal wheel of low efficiency and heavy weight is to be discarded [1, 2].

Thus, one obviously has to give up the advantage of the considerable sturdiness of the wheel itself.

The more suitable "aeronautical" type structure is a mixed one of wood and metal [12] with partial framework over the rear part of the profile, which is under less stress. The durability of this part is limited to 2-3 years, but repainting and substitution is very easy.

The wheels of wind-electric power plants must be constructed with blades of variable inclination. This is because:

⁵See Panunzio, op.cit. However, it is not so with the Tripolitan hinterlands.

1) It is necessary to guarantee a previously fixed angular velocity, or at least a good efficiency of the windmill-generator unit for variable V within wide enough limits. With fixed-blade wheels, one would come to decrease the total efficiency of the plant for certain conditions, not only with synchronous or asynchronous generators, but also with a D.C. dynamo. Only timely variations of the pitch enable correction of this disadvantage, as in the case of hydraulic turbines or the Kaplan airscrew.

2) The starting torque with high-speed wheels of small pitch (necessary for driving electrical generators which in addition still require a multiplier) is by itself insufficient and requires transitional variation of the pitch for each start, which, given the variability of the wind, is probably at every instant [13].

In addition, during the moments of "pause," the wheel requires a setting at zero pitch for achieving minimum retardation and avoiding a halt in the output supply.⁶

3) For reducing dangerous maximum running speeds in small power plants, we use belt slippage, automatic clutch disconnection, demagnetization-type series windings, etc.

For wind-electric plants of a certain power output, there is no other way but timely regulation of the pitch that would diminish the receivability of the wind energy on the wheel at /496 the moment of greatest danger.

For large wind-driven rotors, the blades are generally controlled indirectly by means of fins or control surfaces, a system used in various helicopters and adopted at Balaclava.

⁶As is better explained in the publication [15], it is also necessary to use adequate fly-wheels for regulating the motion.

But for reasons of economy, we must absolutely exclude the intervention of continuous surveillance, and therefore the regulatory service must be provided automatically.

In general, we use an accessory apparatus operating on an electrically or anemometrically controlled servomotor, which still becomes costly, complicated and not completely effective.

Having studied the problem very closely, I maintain that it is necessary to achieve an automatic system which is more intrinsic with respect to the blade itself, eliminating the central servomotor outright.

From this derives, as we will soon see, a considerable simplification of the power plant, which not only involves the wheel, but also makes the construction of the support pylon or tower less costly.

The principle of the wind-vane type blade, already adopted as a safety device in Simplex, Bilau and other air motors, is very well known.

The blade, suspended on the radial axis 0 (Fig. 1), is formed by a piece of sheet-metal with a curved forward edge, which braces 0. The resultant aerodynamic effect of V (relative wind), i.e. F_a , gives rise to a moment which tends to increase the pitch.

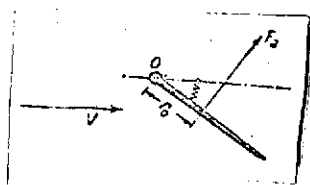


Fig. 1.

$$M_a = F_a \cdot r_0 = C \cdot s \cdot W^2 \cdot r_0$$

where r_0 is the arm, s the surface of the blade element considered, W the resultant wind velocity and C the relative aerodynamic coefficient, as a function of the angle of attack or incidence of the blade.

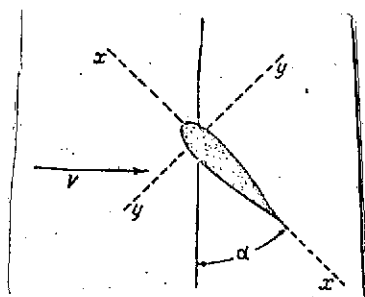


Fig. 2.

If, as is seen in Fig. 1, M_a is countered by a spring and the wind increases, M_a increases, and the pitch obviously decreases; thus, the angular velocity is consequently moderated.

On this principle are based numerous patents for aircraft propellers, ship screws, turbines, etc. But the use of springs and similar devices, not very practical in every case, is to be excluded for giant rotors.

Under a more reasonable principle in various automatic propellers, for example the Parmentier type, one uses for counterbalancing M_a the opposing moment of the centrifugal force acting on the mass of the blade, which, through the well-known resolution of the forces, always tends to diminish the pitch or inclination of the rotating blade α (see Fig. 2).⁷ This moment is defined [14, 15] as:

$$M_f = (I_y - I_x)(R - R_0)\Omega^2 \sin 2\alpha$$

where I_x and I_y are moments of inertia of the section considered with respect to $x - x$ and $y - y$, Ω is angular velocity of the wheel and $R_0 - R$ are radii of the end sections of the blade, which is assumed to be plane (α is constant along the radius).

The pitch regulation, as I have demonstrated [14, 15], is in this system determined by a suitable coefficient and is almost independent of the angular velocity of the wheel.

The pitch increases or decreases with corresponding variations in V , but the equilibrium $M_a - M_f = 0$ with α variable is

⁷Through this effect, the moment in question disturbs the controlled regulation and, as is seen in photographs of the Balaclava plant, the blades are equipped with heavy compensatory masses.

only achieved with variations of the aerodynamic coefficient C , which is to say of the incidence, because W^2 and $\sin 2\alpha$ have variations which are generally concordant but of different value.

This is an inconvenience, because with C variable, the coefficient of aerodynamic efficiency, which has an influence on the efficiency of the wheel, varies.

In spite of this, through an extensive study of the system and with suitable dimensioning and distribution of mass in the blade, it is possible to obtain the desired results equivalent to those obtained up to now with a complex and costly servomotor designed for regulating the pitch of the wheel. A long experimental process has enabled us to find effective solutions to this important problem. It would, however, take too long to explain here in detail how these results were obtained, and I intend to do this exhaustively in another publication in the future.

But I think it would be interesting to explain here, if only briefly, how the system of the intrinsic autoregulation of the blade ((with the exclusion of the central servomotor) offers other major advantages.

If one adopts, as in Fig. 2, a blade with a symmetrical biconvex profile (by now recognized as optimal in every respect), it is easy to show that the wheel does not change direction of rotation if the air current is reversed, even if the pitch of the airscrew is reversed automatically.⁸ In addition, the wheel never stops through the effect of its orientation with respect to the wind, as it is able to function optimally even in oblique wind.

⁸ And in fact (Fig. 2), if V , instead of arriving from the left, should come from the right, the aerodynamic effect would invert α and the direction of rotation would be maintained, together with every other condition of functioning (symmetry).

I report in Table 2 below the data from my cited work which I determined experimentally with a special windmill. γ is the relation wind velocity / peripheral velocity, ϕ the angle which the wheel disk forms with the direction of the wind; due to factors mentioned above, this can be taken as positive or negative, as desired.

TABLE 2.

$\pm \phi$	0°	10°	20°	30°	40°	50°	60°	70°	80°-90°
γ	2,3	1,8	1,1	0,7	0,43	0,31	0,29	0,25	0,22

It is easy to see that the energy performance of the windmill diminishes with ϕ , i.e. with the obliqueness of the wind. One may observe that with each windmill in oblique wind, the total energy in play varies approximately in accordance with $\sin \phi$, i.e. in parity with V . In fact the flow which traverses the wheel is proportional to the surface of the projection of its disk on the plane perpendicular to the wind.

Apart from this power factor, there is the aerodynamic efficiency of the wheel that should be considered under these special conditions of ϕ . For wheels with fixed blades, and even for those regulated with a central servomotor, this always becomes very low, and becomes zero for $\phi > 30^\circ$. Instead, for wheels with self-regulated blades of the kind indicated, which undergo periodic regulation during the circular run of each revolution, high efficiency is always maintained. /497

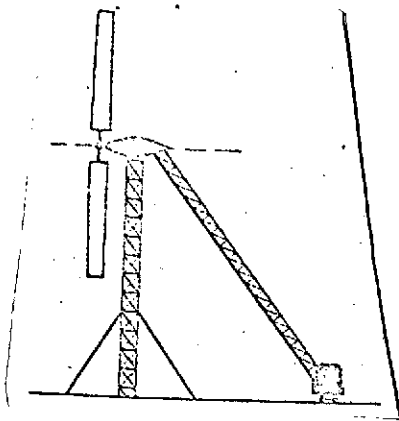


Fig. 3.

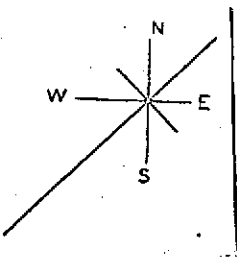


Fig. 4. Average wind rose in London.

-- something which was achieved in the Balaclava plant with nothing less than a gliding carriage on a circular wheel-track and driven by a very costly servomotor.

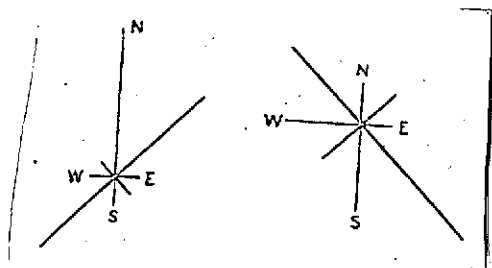


Fig. 5.

of the mountains stopping or diverting the winds. For example: on the left in the figure is the average wind rose in Florence; on the right, the same in San Giovanni in the Arno valley.

With reversibility and a high efficiency for different ϕ , there is now the possibility of making the wind-electric installation fixed, eliminating the costly rotating platform or any orientation device.

For giant support pylons the structural difficulties are very serious, because the enormous stresses in play require the adoption, as seen in Fig. 3, of a triangular system formed by an almost vertical central reticular beam combined with another inclined beam which must "follow" the wind

Figure 5 shows that Italy is dominated by N-NE-SE-S-SW-NW winds. But there are effective local situations which are very different even between short distances, something which is easily explained by the influence

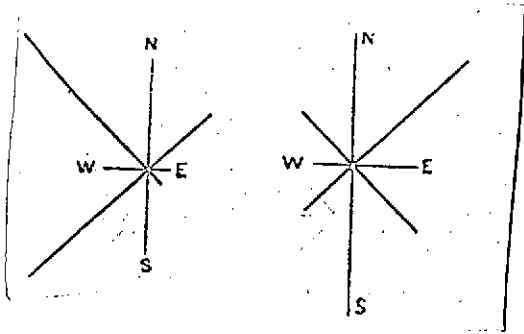


Fig. 6.

On the left of Fig. 6 is the average wind rose in Messina. On the right, the average wind rose in Venice with NE and S-SE prevailing. These latter winds become prevalent in a more decisive form on the Adriatic coast. In the

hinterland, at Padua, the NW wind instead assumes importance.

Instead of the system shown in Fig. 3, a power plant with a reversible wheel with self-regulated blades becomes infinitely more simple, due to the fact that the inclined reticular blades can be fixed, to become alternately a tie-bar or a strut, according to the direction of the wind.

It may be noted that there exist anemological conditions ^{/498} that are perfectly suited for this system. They are the extended wind roses (e.g., Fig. 4: average wind rose in London) for which even the most imperfect utilization of lateral frequencies (low ϕ) leads to limited losses easily compensated by a wider dimensioning of the wheel.⁹

In certain cases, it is possible to give the wheel itself a limited orientability (sector of 40-90°), which serves to cover the wind rose almost entirely even for more complex roses (see Figs. 5-8).

The economy achieved with such devices is notable, since

⁹Many winds are reversible: sea and land breezes, the monsoons in Italian Somaliland, etc. In Tuscany, the prevailing SW wind combines with N and NE currents, and so on.

the pylon constitutes a major part of the power plant. It can reach up to 15-20% reduction in the total expenditure of the plant itself.

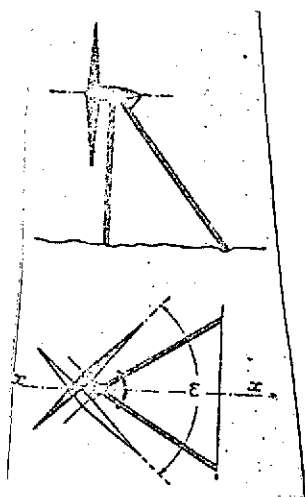


Fig. 7.

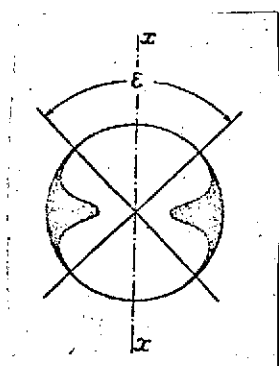


Fig. 8.

Figure 7 shows the scheme of the ^{/497} pylon for reversible wind-driven wheel with limited orientability, seen laterally and in plane. It consists of two resisting triangles (constructed with wooden beams for wheel diameters of up to 10-12 m; and with slender metal trelliswork for greater diameters). The wheel generator unit can rotate at angles of up to 90° under the control of a common orientator windmill.

Figure 8 shows a radial diagram of wind utilization with the pylon shown in Fig. 7. Thanks to its reversibility, there is full efficiency in two of the quadrants (ϵ and opposite the vertex). Good utilization with the minimum of coefficient 0.45 is found in the other two quadrants. The losses (in black) are minimal if the x-x axis is well-oriented on the wind roses in Figs. 4, 5, and 6. They can be compensated with an increase in the wheel diameter of less than 10%.

The curve in full line (Fig. 9) indicates frequency f (days per year) as a function of the wind velocity in m/sec. The maximum of the frequency coincides in general with the average

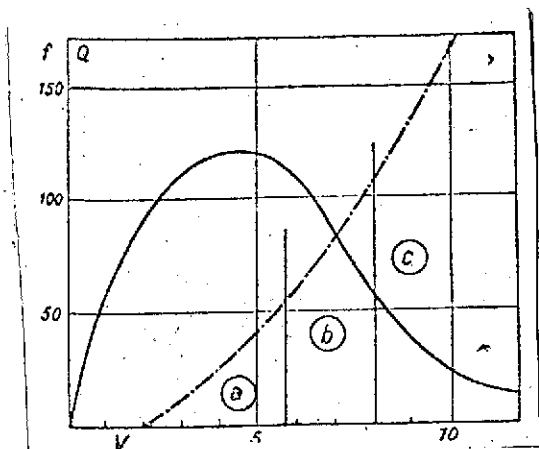


Fig. 9.

velocity of 4-6 m/sec. From this curve, by multiplying the ordinates by V^3 and calculating the efficiencies and their variations, we get the curve in dot-and-dash line which determines the annual energy as a function of V . Through integration, we can obtain the available energy for defined frequency zones and thus determine a rational utilization scheme of the plant's output.

It may be noted that there are about three zones, which are:

a) maximum frequency: suitable for charging storage batteries of a lighting system. In a multipurpose wind-electric plant of a certain power, the drawing of power only at maximum frequency for the above charging reduces the battery capacity.

b) average frequency: (also the same as a). It is suitable for lifting water, mills, sawmills, etc., which require little power and permit noncontinuous use limited to 2-3 days per week.

c) minimum frequency: for irregular operations of a seasonal nature at maximum power, such as ploughing during the windy months of March and October, for terrain cultivation, oil production, etc.

This involves services that are very well adapted for certain agricultural operations for which the use of the communal power distribution networks is not economical, due to the low rate of consumption.

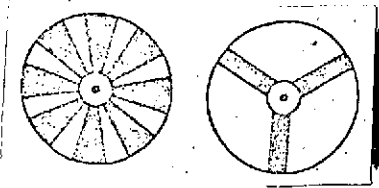


Fig. 10.

In Fig. 10, given the greater /498
functioning amplitude which a wind-driven wheel requires in comparison with its screw-shaped hydraulic counterparts, a variation of the total blade surface is shown to be necessary, apart from the pitch variation.

In a wheel of constant angular velocity, the optimum blade arrangement varies as indicated in the two schemes, which is to say a velocity of 2 m/sec on the left and 10 m/sec on the right.

In general, however, it always approaches the first shape, which is structurally more convenient and thus sacrifices little efficiency for high velocities whose irregular nature requires less consideration.

Conclusion

The problem of wind-electric power plants of certain power capacity (15-100 kW) is moving toward practical solutions which do not neglect the important economic factor always prevalent in industrially oriented questions.

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